Proposal for a new neutron detector

High efficiency neutron counter for studies of β-delayed neutron emission

spokepersons :

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in collaboration with

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1 Introduction

It is proposed to construct a high-efficiency, high granularity neutron detector array. This detector will allow us to study the properties of beta-delayed neutron (β-n) emission from very neutron-rich nuclei, help to identify new neutron-rich isotopes, and measure their beta decay halflives. The measurements will include a determination of absolute β-n branching ratios $I_{\beta-n}$ and neutron emission to the excited states.

The high-efficiency of the neutron array is vital for the study of low intensity radioactive beams. The segmentation and high-efficiency of the proposed neutron counter is particularly important for the detection of two simultaneously emitted neutrons, i.e., discovery of β-delayed two-neutron emission from heavy nuclei. Both decay modes, the β-n and β-2n emission, affect the isobaric distribution of nuclei created within the rapid neutron capture nucleosynthesis process (r-process).

The neutron detector will be assembled, commissioned and used in experiments performed primarily at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory. It will be used at the HRIBF with postaccelerated radioactive ion beams (RIBs) of neutron-rich nuclei produced in proton-induced fission of an UC_x target [1, 2]. Postacceleration of mass-separated beams in conjuction with the novel "ranging-out" technique, developed at the HRIBF [3], offers isotopically pure beams of known intensity. A continuous event-by-event monitoring of beam intensity is particularly important for the determination of absolute β-decay branching ratios, including $I_{\beta-n}$ values.

The neutron detector will be based on commercially available, 1" and 2" diameter tubes filled with ^{3}He at 10 atm pressure. The ^{3}He tubes will be embedded in an axially symmetric 2-foot long cylinder, made out of a High Density Polyethylene (HDPE) moderator, see Fig. 1. The most important feature for the determination of absolute $I_{\beta-n}$ values is a high and nearly constant efficiency for low energy neutrons (<2 MeV). The efficiency of the neutron detector was simulated to be nearly constant, around 75%, between 0.01 MeV to 2 MeV, see Fig. 2. The proposed counter is also very efficient for counting higher energy neutrons, with efficiency above 50% at 5 MeV. The postaccelerated "ranged-out" radioactive ions will be deposited onto the Moving Tape Collector (MTC) [4] in the middle of neutron detector. Beta detectors and X-ray or clover γ-counters will be placed in an adjustable opening along the detector axis. Such flexibility will allow us to optimize the low-energy vs high-energy gamma counting without compromising the detection efficiency for emitted neutrons. Neutron transitions to excited states will be identified via neutron-γ correlations obtained with the X-ray or γ-ray detector. Digital XIA electronics [5, 6] coupled to ORTEC preamplifiers will analyze the signals from the ^{3}He tubes as well as from beta and gamma detectors.

The proposed design offers higher efficiency in a similarly compact shape compared to existing ^{3}He neutron counters, such as the Neutron Emission Ratio Observer (NERO) [7] operating at the NSCL and K.-L. Kratz's "Long counter" [8] used in Europe. The current design has a much higher efficiency and lower energy threshold in comparison to the large-scale time-of-flight neutron detector array "Tonnerre" [9] built recently in France. The compact shape of the neutron detector makes it transportable. In addition to the experiments at the HRIBF, it can be used also at the NSCL and, in the future, be ready for the experiments at the Rare Isotope Accelerator (RIA) laboratory [11].

The HRIBF is a user facility. The experiments are performed within large collaborations involving graduate students. In particular, several university groups in the UNIRIB Consortium are actively collaborating in the decay spectroscopy studies. Students from UT, Vanderbilt, Lousiana, Mississippi, Notre Dame, Colorado School of Mines and other colleges will obtain significant hands-on experience with low-energy neutron counting, and understand the properties of neutron emission and detection. HRIBF will be the only user facility performing the decay studies of beta-delayed neutrons emitted from fission products.

We will elaborate below on the points briefly mentioned in this section.

2 Motivation

Studies of neutron-rich nuclei are among the primary directions of low-energy nuclear physics. Such investigations should test new predicted features of nuclear structure in neutron-rich matter as well as provide important data on neutron-rich nuclei necessary for astrophysical modelling of stellar evolution.

The probabilities of beta transitions for exotic nuclei are presently calculated using the properties of neutron and proton single-particle orbitals established for nuclei close to beta stability. The modification or even quenching of shell structure for very neutron-rich nuclei will change the distribution of the beta strength function in the decay energy window Q_β. It will also affect beta decay probabilities and related beta-delayed neutron branching ratios $I_{\beta-n}$. These are the primary input parameters in the modelling of the nucleosynthesis of heavy elements within a rapid neutron capture process (r-process). In particular, the β-halflives and $I_{\beta-n}$ values, together with neutron capture cross sections, govern the predictions of final isotopic abundances. These isotopic abundances are measurable with present observational techniques even for very exotic distant objects (see, e.g., recent news on a NASA experiment involving a comet impact and analysis of stellar debris).

Interpretation of measured isotopic distributions contributes to the identification of the site and the mechanism of the r-process. Understanding of the r-process cannot be achieved without the correct decay properties of neutron-rich nuclei used as input parameters for the astronuclear modelling.

Beta-delayed neutron emission quickly becomes an important decay mode for neutron-rich nuclei having a neutron separation energy, S_n, of a few MeV, see Fig. 3. There is no Coulomb barrier slowing down the decay process, so the opening of the $Q_{\beta-n} = Q_\beta$ - S_n energy window facilitates neutron emission. However, even with a wide $Q_{\beta-n}$ window the beta transitions to lower energy states are favored, and the emission of low energy neutrons dominates the decay.

Practically every proposal on the decay studies of neutron-rich nuclei submitted to the HRIBF points to the advantages of β-delayed neutron detection and the need for such a detector at the HRIBF. In particular, the PAC-accepted experiments on beta decay properties on ^{76}Cu and ^{77}Cu [12], on ^{83}Ga [13], on ^{86}Ge and ^{87}Ge [14] ALL aim at the study of beta-delayed neutron precursors. Counting of beta-delayed neutrons was also pointed out as one of the main goals of the project to study the decays of neutron-rich Bromine isotopes [15].

Currently, the measured $\beta - n$ branching ratio reported by different experiments often vary significantly or only the lower limit of the $I_{\beta-n}$ is derived from the data, see Fig. 4 and Fig. 5. This is related to the often unknown absolute efficiency of the neutron counters, especially at low neutron energies, the unknown beta branching ratio for ground-state feeding, and the unknown number of decaying isotopes in the studied samples. There is an obvious need for reliable data on β-n emission properties deduced using independent spectroscopic methods and neutron-rich beams of known intensity. The available data on Copper isotopes, one proton above magic nickel nuclei and near the starting region of the r-process, illustrate the problem. The systematic analysis of β-n emission process is difficult since the experimental value of β-n branching ratio for Cu-isotopes was measured for only two out of six known β-n emitters, see Fig 4. The yields of Cu-isotopes available at the HRIBF will allow us to verify and measure the $I_{\beta-n}$ values for six Cu isotopes, from A=74 to 79, see Fig. 6.

The availability of purified (postaccelerated and "ranged out") radioactive beams of measured intensity [3] is a unique feature of the HRIBF. The "ranging-out" method utilizes the fact that for a beam of neutron-rich nuclei at a given mass number A the higher-Z contaminants have a smaller range in matter. The beams are passed through an ionization chamber which acts as an active degrader and allows the identification and determination of intensity for the ions using energy loss, ΔE, and total energy, E, signals [3]. By increasing the gas pressure in the ionization chamber the higher-Z components (produced at high yields) are stopped in the chamber. The most neutron-rich (lowest-Z) ions have the longest range and are transmitted beyond the gas cell to the decay spectroscopy station, to be equipped with the proposed neutron counter. The "ranging-out" technique combined with beta, gamma and neutron counting can verify and extend the existing $I_{\beta-n}$ data base.

Other methods of radioactive beam purification, available at the HRIBF, are also relevant for the measurements of β-n emission. The experiments involving the counting of beta-delayed neutrons can start with readily available isotopically pure neutron-rich Bromine and Iodine beams [16]. As an example, Fig. 7 shows the yields of Bromine isotopes released from surface ionization LaB_6 ion source, free from isobaric contaminations. There are eight Bromine isotopes (A=87 to 94) and six Iodine isotopes (A=137 to 142) produced at the rates above one ion per minute at the HRIBF which emit β-delayed neutrons. Additionally, the molecular ions SnS and GeS can be extracted from the HRIBF target/ion source system [1]. This purification technique will allow us to measure the properties of β-n emission for at least five Sn isotopes (A=133 to 137) and for four Ge isotopes (A=84 to 87).

With pure beams and the high-efficiency of the proposed neutron counter, the identification of decay properties of new isotopes is clearly within the reach of HRIBF. For the radioactive nuclei with millisecond halflives, few ions per hour are sufficient for the identification of new activity. Such a measurement is facilitated by the high-efficiency of the neutron counter and short time correlations (implant - decay) reducing background events. Once the experimental technique is optimized and the response function of neutron counter is verified, we continue the measurements aiming at a wider spectrum of neutron-rich nuclei.

Further developments in radioactive ion beam production at the HRIBF including the completion of the High Power Target Laboratory and its coupling to the present RIB facility will help extend our reach to new neutron-rich nuclei. A new decay spectroscopy station, under development after the high resolution RIB injection magnet, offers another place for using the neutron counter and will profit from the full intensity of the HRIBF RIBs. Since this decay station is located before the Tandem accelerator requiring negative ions for postacceleration, we will use also positive ions extracted from the ion source. It makes the range of elements accesible for beta-delayed neutron studies much broader.

3 The design

The design criteria of the neutron detector included a high neutron detection efficiency with a flat response to low-energy neutrons, a small outer diameter enabling it to easily fit inside existing support structures, system portability and a flexible construction that would allow for the use of auxiliary beta and gamma detectors.

Several possible designs were considered, including variations with respect to the moderator material and size, the gas pressure, length, diameter and number of the ^{3}He tubes as well as the total cost of the detector.

The design presented here, see Fig. 1, was selected based on the criteria listed above. The detector efficiency and response function [18] was simulated using the Geant4 [19] code. Comparisons between the results of Geant4 and Monte Carlo N-Particle (MCNP) [20] simulations were carried out. The obtained efficiencies were found to be in reasonable agreement (within a few percent). The high efficiency, nearly constant for important low energy neutrons, see Fig. 2, was achieved while retaining a reasonably compact device at a cost of $350k.

The neutron detector consists of four rings of ^{3}He tubes, surrounded by HDPE acting as the moderator. The current maximum efficiency, of about 79%, is limited only by neutron capture on hydrogen atoms present in the HDPE. In an attempt to reduce the effect of neutron capture on hydrogen atoms, further simulations were conducted with heavy-water (D_2O) as a moderator. The replacement of the HDPE by D_2O reduced the total efficiency by about a factor of five for the same moderator size, mostly due to the side-leakage of neutrons. The increased side-leakage results from the less efficient moderation of neutrons by D_2O compared with HDPE. The utilization of D_2O would lead to an unacceptably large detector.

There are sixteen ^{3}He tubes of 1" diameter in the inner ring, and a total of fifty eight 2" diameter tubes in three outer rings. A 2-foot length was selected for the tubes. An extension of the length to 3 feet increases the cost of the tubes by about 50%, but doesn't increase the efficiency by more than 1 percent to 3 percent (for 5 MeV neutrons). Simulations show that this small increase in efficiency for higher energy neutrons is due to a partial reduction of a small end-leakage of neutrons from a 2-foot detector. It means that the cylindrical detector shape surrounding the centrally located source approximates a spherical geometry fairly well (2-foot diameter and 2-foot length).

The central hole of the detector, nominally 9 cm in diameter (Fig.1), can be varied by changing an inner HDPE annular insert. The 9 cm hole accommodates two 2π plastic beta detectors surrounding the 2" thin-wall beam line pipe.

An auxiliary X-ray or gamma-ray detector, like the LOAX ORTEC detector or a 45% GammaX ORTEC detector, both available at the HRIBF, also fit into the 9 cm hole. A different insert enables the use of a larger 140 % EURISIS clover γ-detector. This clover will be used for the studies of very neutron rich nuclei, when the detection of higher energy photons in correlations with emitted neutrons becomes increasingly important. The observation of neutron feeding of excited levels will allow us to deduce the probabilities for neutron transitions of different angular momentum. The location of the inner ring tubes, with a tube edge at about 7.3 cm from the detector axis allows us to accommodate a rectangular clover shape corresponding to a maximum radius of 7.1 cm.

The simulations of the response function per detector ring, see Fig. 8, show that the spectrum of neutron energies can be at a minimum separated into four bins by comparing the measured neutron intensities per ring. This is not as precise measurement as could potentially be offered by a time-of-flight counter (much larger and much less efficient [9]), but gives an estimate of the contribution from high energy neutrons.

The layer of at least 1 inch of HDPE between the neutron source and first ring of ^{3}He tubes enables the slowing and very efficient counting of low energy neutrons, see Fig. 2 and Fig. 8. The HRIBF studies are foreseen to start with first βn emitters for given element (low energy neutrons emitted), and proceed towards more exotic isotopes.

To reduce background neutrons present at the accelerator facilities, additional shielding will be required. Plates of 1 mm Cadmium surrounded by the HDPE and paraffin bricks will be placed around the neutron counter. The detector will be mounted inside a standard CARDS support frame [4] manufactured at LSU (two frames already available at the HRIBF).

4 Comparison with existing detectors

There are presently only two ^{3}He detectors actively used in decay studies involving the detection of beta-delayed neutrons.

The "long-counter" constructed over 20 years ago by the group of K.-L. Kratz at Mainz (Germany) has been successfully used in the European laboratories, including CERN-ISOLDE

(Switzerland), GANIL (France) and GSI (Germany). It has HDPE housing, with a 100 mm diameter central hole, and a side hole for insertion of a germanium counter perpendicular to the beam axis. The latter opening reduces the number of usable ^{3}He tubes to about 50. These tubes, 3 feet long and 1" diameter, also operate at 10 atm gas pressure [8]. The efficiency of the "long counter" shown in Fig. 9 was calculated using Geant4 employing the geometry described in [8]. The proposed HRIBF detector is about 50% more efficient in comparison to the "long-counter".

The Neutron Emission Ratio Observer (NERO) operated at the NSCL [7] has an even larger central opening (about 20 cm diameter) to accommodate the NSCL beta telescope [21]. The efficiency curve, see Fig. 9, simulated with the MCNP code can be found in [7]; NERO has only about half of the efficiency of the proposed HRIBF detector.

The β-n energy spectrum can be measured using a neutron time-of-flight (nTOF) technique [9, 22, 23]. The "Tonnerre" array [9] is the most recently built nTOF detector. However, this device, about 2 meters long and over 2.4 meter in diameter, has much higher energy threshold for detecting neutrons (about 1 MeV) and total efficiency which is only about 15% at the maximum around 2 MeV [9]. The nTOF-arrays are well suited for measuring beta decays of **light neutron rich nuclei** followed by the emission of monoenergetic neutrons, e.g., the decays of ^{15}B, ^{16}C and ^{17}N were used to verify the performance of "Tonnerre" array [9]. The experiments on ^{17}C and ^{18}C [24], on ^{11}Li [22], and most recently on neutron-rich Nitrogen isotopes up to ^{22}N [25] are the examples of heavy-ion fragmentation based studies using nTOF spectroscopy at the NSCL. Very recently at TRIUMF/ISAC, twenty plastic scintillators were used together with the "8π" γ-array to study the decay modes of ^{32}Na [23]. However, the proposed HRIBF neutron detector will be used primarily to derive the absolute branching ratio for beta-delayed neutrons from **heavy nuclei produced in fission**. The neutrons can be emitted with energies even below 100 keV, and have a continuous spectrum of energies due to the high level density at higher excitation energies in heavy nuclei.

The ^{3}He-based counters including proposed multidetector array are free from the scattered neutron "false counting" effect since the neutron is captured in the resonance reaction ^{3}He(n,p)t. It is particularly important for an identification of the β-2n decay mode in the presence of more intense β-n emission. The scattered single neutron can produce two simultaneous signals in the adjacent detectors of the nTOF array leading to a misidentification of the β-n events as β-2n signals.

5 Cost estimate

The total cost of the proposed digital β-delayed neutron detector, with tax and overhead included is **$ 348,000**. A dedicated stand-alone data acquisition system would cost an additional $ 100,000.

The total cost includes :

1. ^{3}He tubes at 10 atm gas pressure

- 16 inner ring tubes, 1 inch diameter : $ 17,840
- 58 outer rings tubes, 2 inch diameter : $ 136,000

subtotal with tax and overhead : $ 190,000

2. HDPE detector housing

- seven 4 inch thick, 27 by 28 inch blocks : $ 5,000
- moderator machining : $ 8,000

subtotal with tax and overhead : $ 20,000

3. Cadmium shielding (Mayco Inc.)

- Cd sheets, 1 mm thick, 1.5 by 3 feet : $ 4,800

subtotal with tax and overhead : $ 7,200

4. Preamplifiers

- ORTEC 142IH model, seventy five preamps, $ 600 each : $ 45,000

subtotal with tax and overhead : $ 65,000

Commercially available ORTEC preamplifiers were tested with 2 inch diameter, 6-foot long ^{3}He counters at 4 atm and 10 atm gas pressure using digital electronics (40 MHz Digital Gamma Finder XIA modules). The observed energy resolution was $\approx 4\%$ fwhm, two times better than the factory specifications. The ORTEC 142IH preamplifier is designed to safely handle the high voltage (about 2 kV) necessary for the operation of ^{3}He tubes.

5. High Voltage units (Wiener-ISEG HV)

- 7U HV crate with 8 slots and CAN-bus PCI interface : $ 6,000
- five 16-channel cards : $ 27,700

subtotal with tax and overhead : $ 51,000

The Wiener-ISEG HV cards, characterized by an excellent high voltage stability, can also serve other decay spectroscopy detectors at the HRIBF like an eight-fold fast timing BaF_2 array.

6. shielding bricks and support structure

material and manufacturing : $ 10,000

subtotal with tax and overhead : $ 15,000

7. Stand-alone data acqusition system.

The operation of the proposed neutron counter can be initiated using the existing digital electronics (40 MHz DGF-4C XIA modules) available at the HRIBF. However, in the future, it would be advisable to have a compact transportable data acquisition system serving the neutron counter and auxiliary detectors. Such a system could be used as a stand-alone experimental set-up at the NSCL. Also, off-line studies can be performed at the HRIBF when the DGF-4C modules are in use for other experiments. The ideal solution is to use 16-channel 100MHz digital Pixie-16 cards from XIA, housed together with the data storage disk and the control computer within one 6U PCI crate. The total cost of such a system, with six Pixie-16 cards and PCI crate also housing the computer and large disk is presently about $100,000 (with tax and overhead).

6 Summary

We are applying to the DOE for $ 348,000 to built a highly advanced digital β-delayed neutron detector. This high-efficiency and high-segmentation detector, will clearly exhibit best-in-class performance. The detector could be constructed within nine months after allocation of the full funding. It will be commissioned and used primarily at the HRIBF with post-accelerated radioactive neutron-rich beams allowing for the determination of the properties for beta-delayed neutron emission from nuclei produced in fission. This adds a wholly new capability with strong discovery potential to the arsenal of experimental tools available at HRIBF, filling an important gap in our capability.

Experiments at the NSCL with fast neutron-rich beams produced in a fragmentation of relativistic heavy ions also are foreseen. The new device will have an efficiency twice as large as the detector now in use at NSCL. This should make possible to study the neutron-rich isotopes of nickel [26], cobalt [27] and iron produced at the NSCL with larger yields in comparison to the HRIBF rates.

In the future, this detector can be directly applied to the research at RIA facility.

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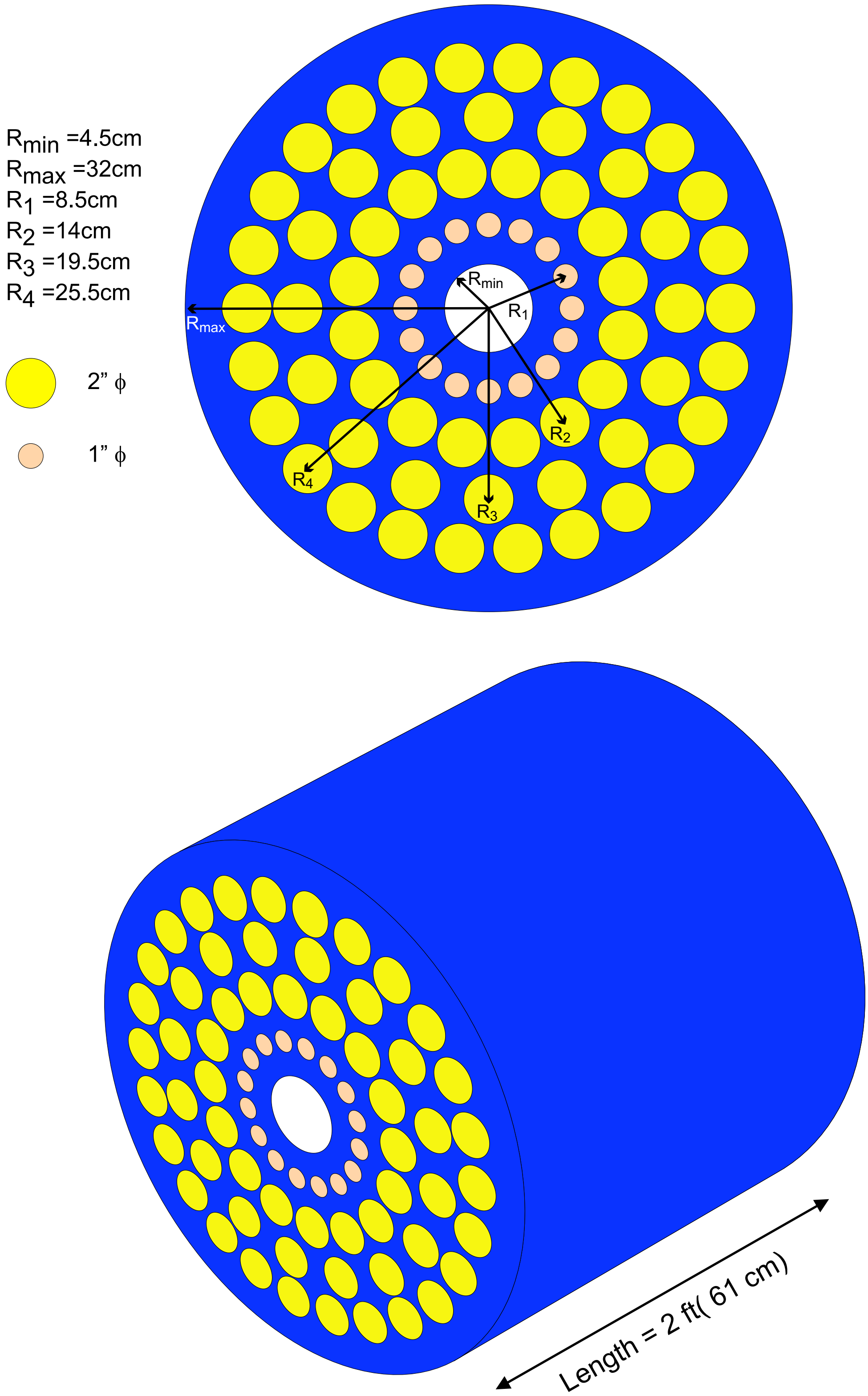

Figure 1: The schematic drawing of the proposed neutron detector. Four rings of stainless steel tubes filled with ^{3}He at 10 atm pressure are surrounded by the HDPE neutron energy moderator/thermalizer.

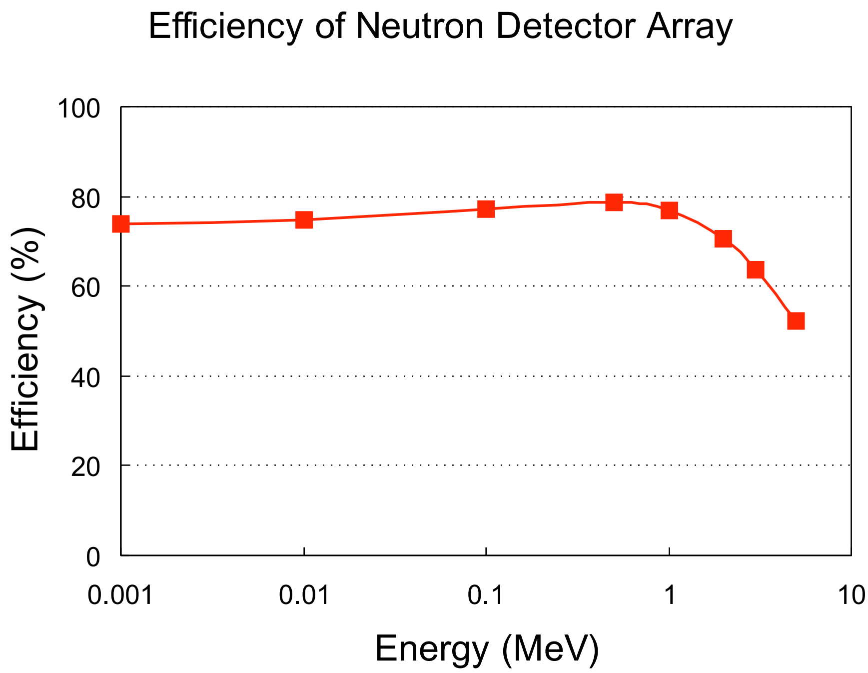

Figure 2: The efficiency of proposed beta-delayed neutron counter as a function of energy of emitted neutron simulated using the Geant4 code.

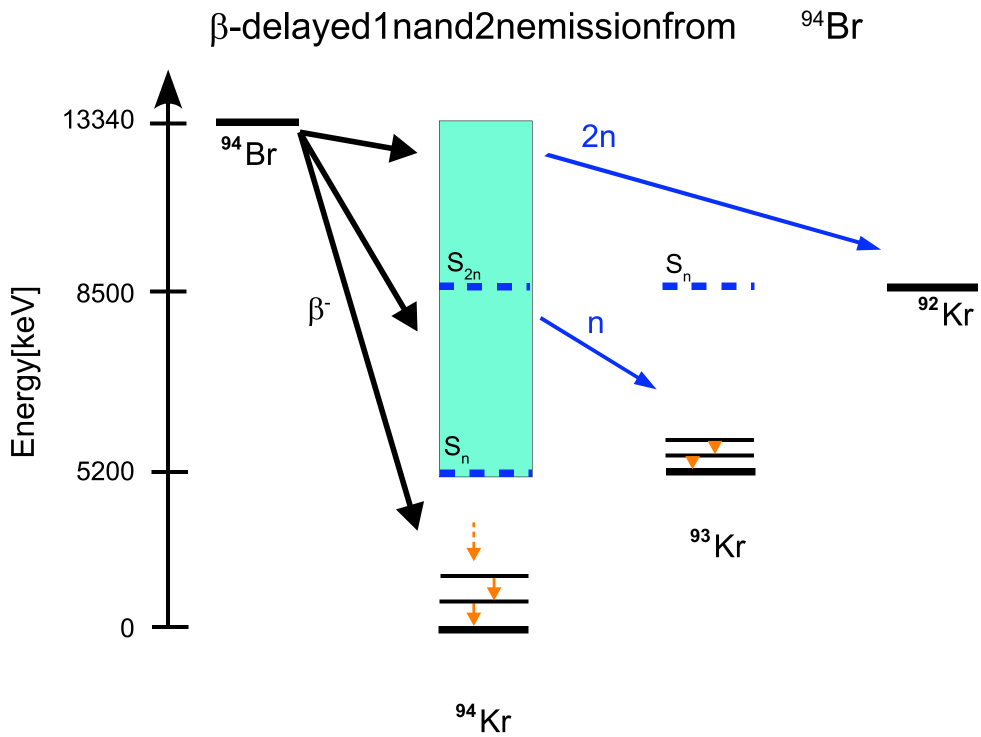

Figure 3: The radiation modes expected to follow beta decay of ^{94}Br. The beta decay energy of ^{94}Br, and the 1n and 2n separation energies in ^{93}Kr and ^{92}Kr isotopes were taken from the extrapolations of measured nuclear masses [10].

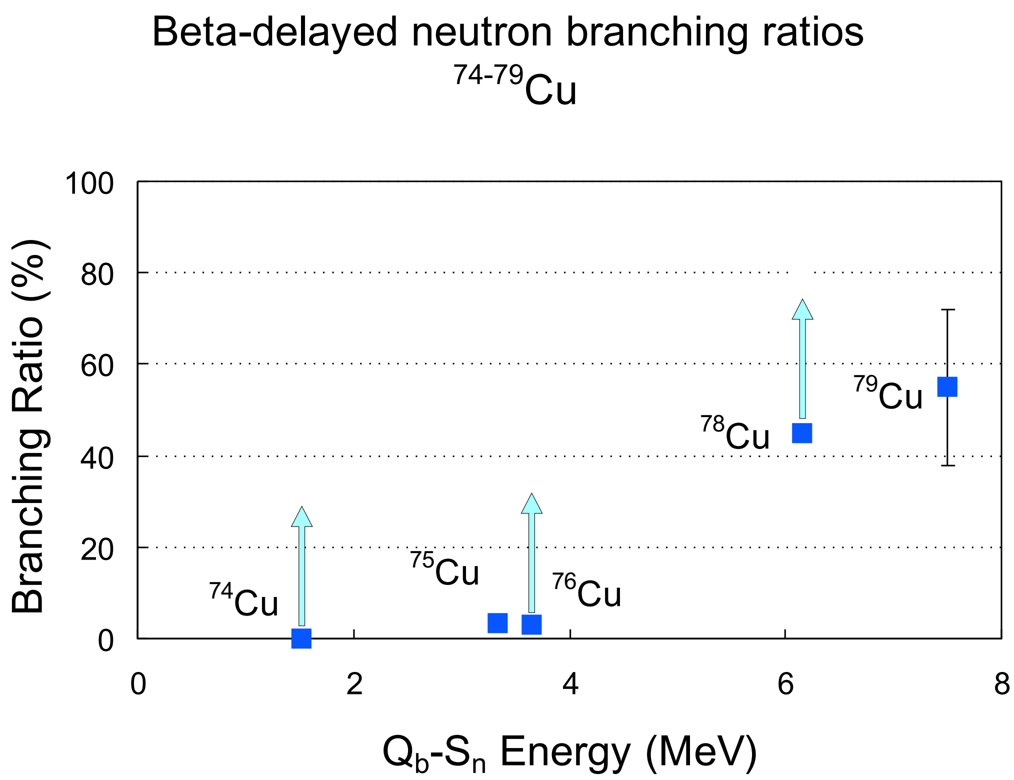

Figure 4: The values of absolute β-delayed neutron branching ratio $I_{\beta-n}$ reported in the literature for the decays of neutron-rich Copper isotopes. The $I_{\beta-n}$ values are plotted as a function of energy window $Q_{\beta-n}$ available for neutron emission. The measured values of $I_{\beta-n}$ were reported only for two out of six Cu isotopes known to exhibit β-delayed neutron emission.

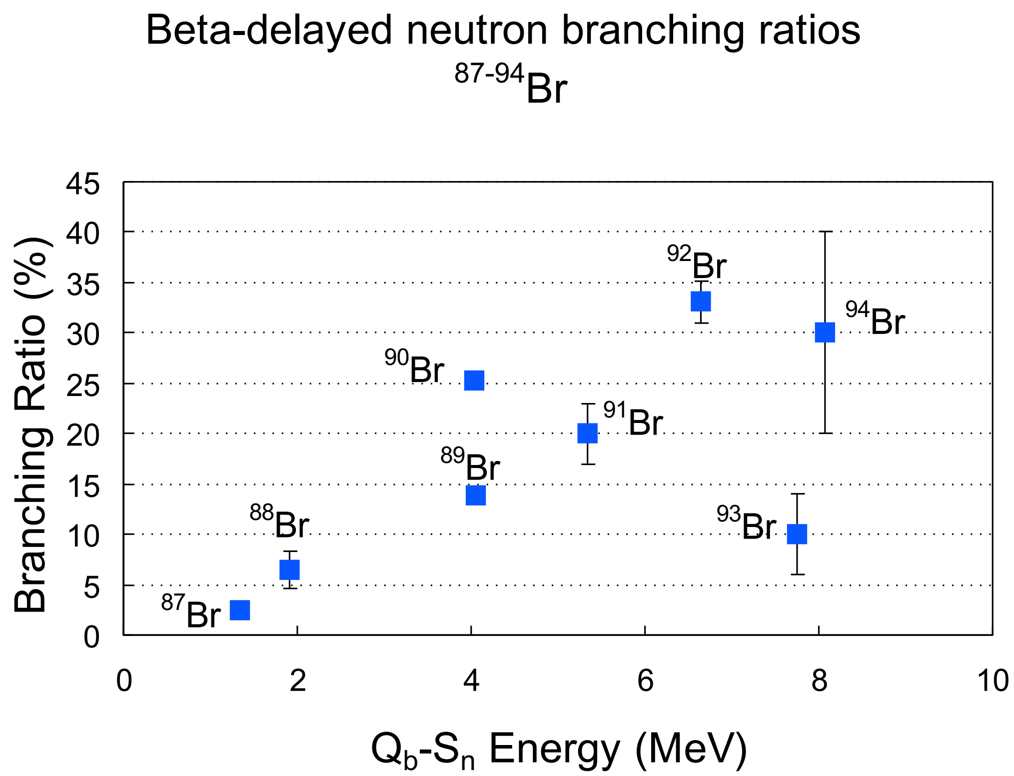

Figure 5: The values of absolute β-delayed neutron branching ratio $I_{\beta-n}$ reported in the literature for the decays of neutron-rich Bromine isotopes. The $I_{\beta-n}$ values are plotted as a function of energy window $Q_{\beta-n}$ available for neutron emission. The result quoted for ^{93}Br is not following the expected pattern of the $I_{\beta-n}$ values increasing smoothly with an increased $Q_{\beta-n}$ value.

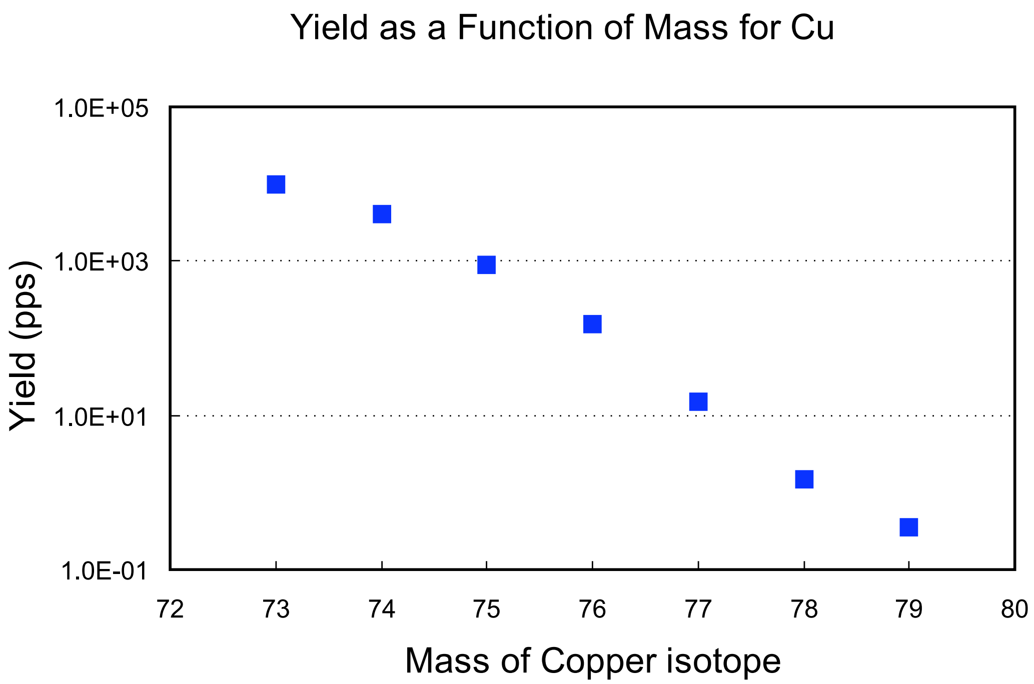

Figure 6: The HRIBF yields of neutron-rich Copper isotopes expected after the postacceleration and ”ranging-out” of higher-Z contaminants [12].

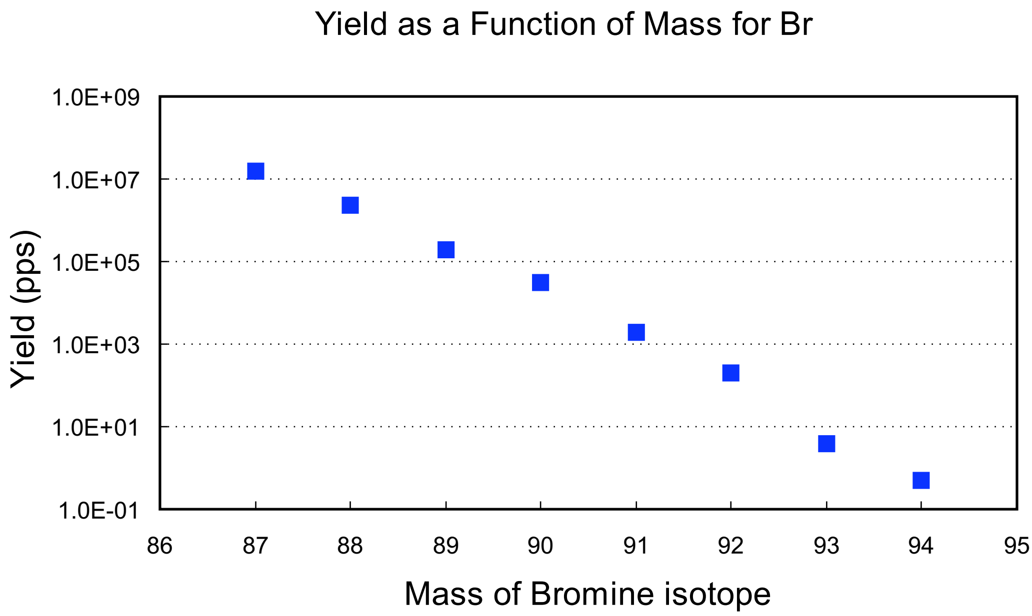

Figure 7: The HRIBF yields of for beams of pure neutron-rich Bromine isotopes expected after a RIB injection magnet before the Tandem accelerator [16]. The production rates were measured for ^{87}Br to ^{90}Br at the HRIBF On-Line Test Facility using 20 nA proton beam from Tandem accelerator and LaB_6 ion source [17]. The displayed results were scaled up to account for the 10 μA ORIC proton beams typically used to generate RIBs at the HRIBF. The yields given for ^{91}Br to ^{94}Br are resulting from the extrapolation presented in [17] and will be verified following the ref. [15] project.

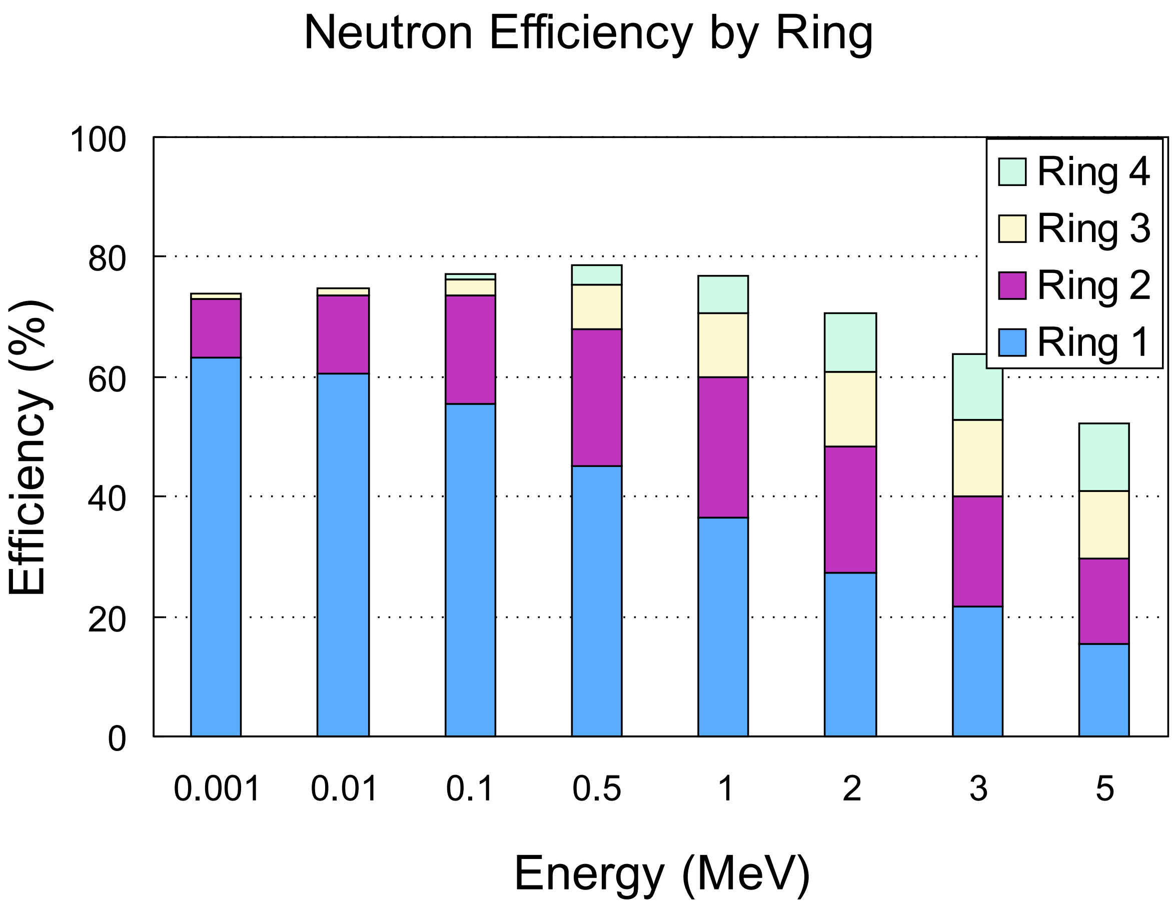

Figure 8: The efficiency-per-ring for neutron detection of proposed neutron counter, as a function of neutron energy. The simulations were made within Geant4 code.

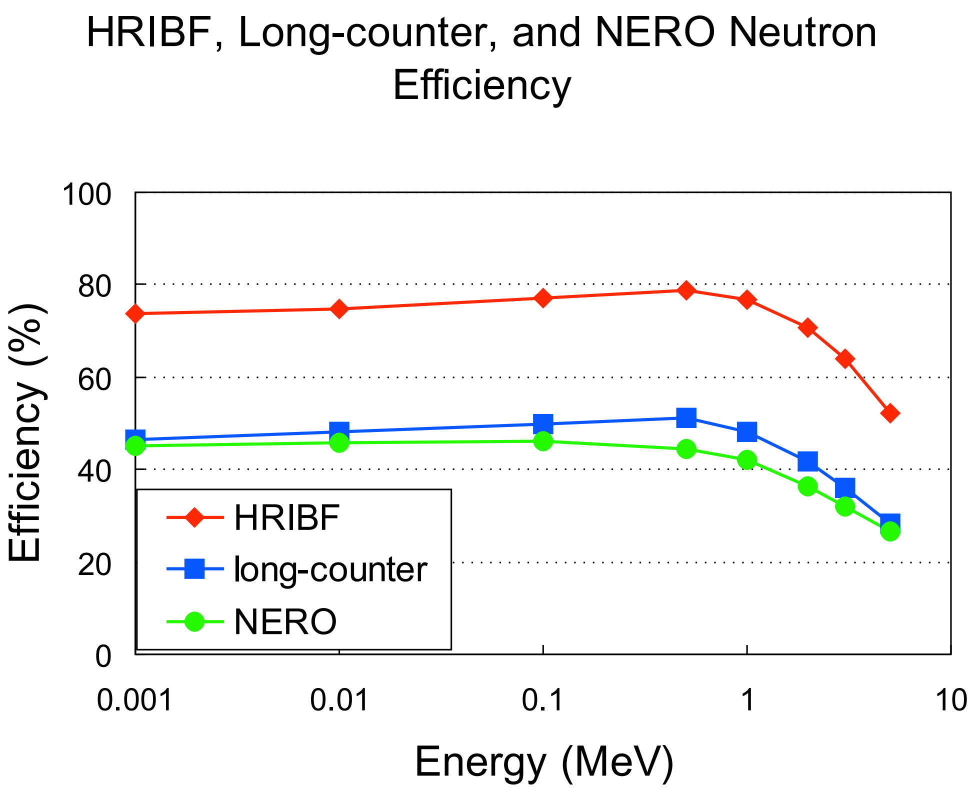

Figure 9: The efficiency curves for neutron detection calculated for the K.-L.Kratz's "long-counter" according to the geometry given in [8] and for the Neutron Emission Ratio Observer NERO [7] compared to the efficiency of the proposed detector.